Received April 6, 2019, accepted May 20, 2019, date of publication May 23, 2019, date of current version June 5, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2918571

Direct Power Control Method With Minimum Reactive Power Reference for Three-Phase AC-to-DC Matrix Rectifiers Using Space Vector Modulation

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This work was supported in part by the National Research Foundation of Korea (NRF) Grant funded by the Korean Government (MSIP) under Grant 2017R1A2B4011444.

ABSTRACT This paper proposes a direct power control (DPC) method with a minimum reactive power reference for ac-to-dc matrix rectifiers using space vector modulation. Based on the calculated active and reactive power reference values, the developed DPC algorithm directly controls both the active and reactive power components of the source by operating the three-phase matrix rectifiers, thereby obtaining the sinusoidal input currents and output dc voltage/current of the rectifier. The proposed DPC method instantaneously determines a source reactive power reference command to achieve a unity input power factor or maximum achievable power factor on given input and output conditions, because ac-to-dc matrix rectifiers cannot always attain a unity power factor due to the existence of the input capacitors. In addition, the developed algorithm calculates the minimum reactive power reference without using any circuit parameters. Thus, the proposed algorithm is free from any inevitable parameter uncertainty, resulting in a more robust and accurate power factor control for the rectifier. Based on the minimum reactive power reference, the proposed algorithm enables matrix rectifiers to operate at an input power factor that can be maximally obtained at all times. The effectiveness of the proposed method was verified by the simulations and experiments.

INDEX TERMS ac-to-dc matrix rectifier, direct power control, minimum reactive power reference, space vector modulation.

I. INTRODUCTION

With the emergence of smart grids, the interest in bidirectional ac-to-dc power conversion systems has increased [1]–[4]. Typical bidirectional ac-to-dc power converters are voltage source converters (VSCs), which exhibit bidirectional power flow, unity input power factor, sinusoidal input current waveforms, and capability of output voltage control [5]. However, because VSCs are boost type converters, additional step-down dc-to-dc converters are required when dc voltages are lower than the ac grid voltage [6]. These cascaded structures can result in an increased volume and reduced efficiency. In contrast, ac-to-dc matrix rectifiers, which are equipped with buck type converters, can lower dc voltages than ac voltages without employing extra dc-to-dc converters, which can improve the overall efficiency and system volume [7]–[11]. The ac-to-dc matrix rectifiers, which are similar to current source converters, have an input LC filter on the converter input side, because of the characteristics of the converter operation [12]. The presence of this LC filter necessitates an additional input power factor control for the matrix rectifiers. In addition, even with power factor control methods, a unity power factor on the source side cannot always be accomplished in all conditions due to the limited modulation index of the rectifiers [12]–[14].

Various direct power controls (DPCs) in ac-to-dc converter including voltage source rectifiers [15]–[19] and current source rectifiers [20]–[24] have been proposed. In the voltage source rectifiers, the DPCs using the switching table shown in Fig. 1 (a) and space vector modulation (SVM)

The associate editor coordinating the review of this manuscript and approving it for publication was B. Chitti Babu.

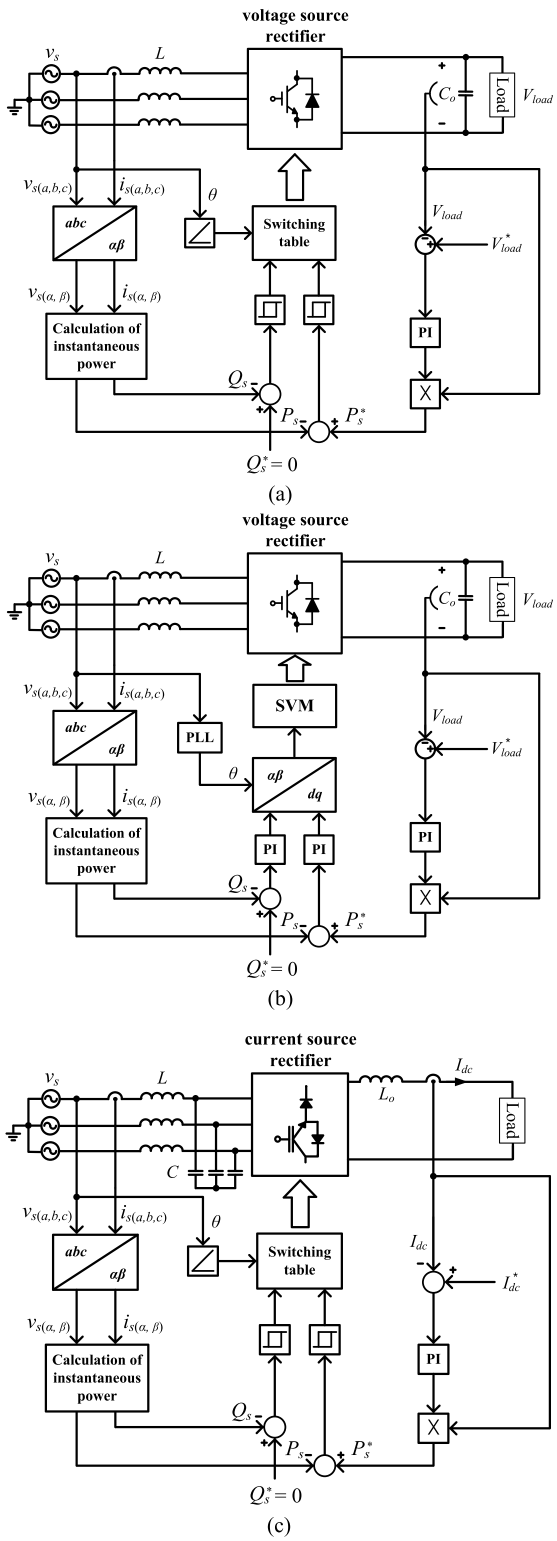

FIGURE 1. Conventional DPC method in ac-to-dc converters. (a) voltage source rectifier using the switching table. (b) voltage source rectifier using SVM. (c) current source rectifier using the switching table.

represented by Fig. 1 (b) were proposed. Since the voltage source rectifiers are not required to install the input capacitors on the input-side, the power factor control problem does not occur in the light load condition. In the current source rectifiers, only the DPCs using the switching table described by Fig. 1 (c) in which the switching frequency is not constant were proposed. As above mentioned, the current source type converters such as ac-to-dc matrix rectifiers cannot achieve a unity power factor at the light load due to the input LC filter. However, existing DPC studies for current source rectifiers attempted to accomplish a unity power factor by setting the reference of the source reactive power to zero without considering the load condition. In addition, the phenomenon that the source reactive power is not zero and a unity power factor cannot be achieved in the light load was not handled. On the other hand, power-based control technique of the current source rectifier has been proposed considering the minimum reactive power in the light load [25]. In [25], a reference for the source reactive power changes to achieve the maximum achievable power factor (MAPF) was designed according to the input and output conditions, in cases where a unity power factor cannot be obtained. Although the input power factor control method based on a varying reactive power reference can successfully achieve a more accurate reactive power control, the reactive power reference, which is calculated using the model parameters including the input LC filter values, can be uncertain because of the inaccurate model parameters.

In this paper, a DPC method with minimum reactive power reference for ac-to-dc matrix rectifiers using SVM which has a characteristic of constant switching frequency is proposed. Based on calculated active and reactive power reference values, the developed DPC algorithm directly controls both the active and reactive power components of the source by operating the three-phase matrix rectifiers, thereby obtaining the sinusoidal input currents and output dc voltage/current of the rectifier. The proposed DPC method instantaneously determines a source reactive power reference command to achieve a unity input power factor or an MAPF on given input and output conditions, because ac-to-dc matrix rectifiers cannot always accomplish a unity power factor due to the existence of input capacitors. Furthermore, the developed algorithm calculates the minimum reactive power reference without using any circuit parameters. Thus, the proposed algorithm is free from any inevitable parameter uncertainty, resulting in a more robust and accurate power factor control for the rectifier. Based on the minimum reactive power reference, the proposed algorithm enables matrix rectifiers to operate at an input power factor that can be maximally obtained at all times. The effectiveness of the proposed method is verified by simulations and experimental results.

II. STRUCTURE AND POWER FACTOR OF AC-TO-DC MATRIX RECTIFIER

Fig. 2 shows the circuit structure of an ac-to-dc matrix rectifier. Here, v_{sa} and i_{sa} represent the a-phase source voltage and source current, respectively; L_{in} and C_{in} denote the inductance and capacitance of the input LC filter of the matrix rectifier, respectively; i_{ia} denotes the a-phase rectifier input current; S_1 to S_6 signify the bidirectional switches;

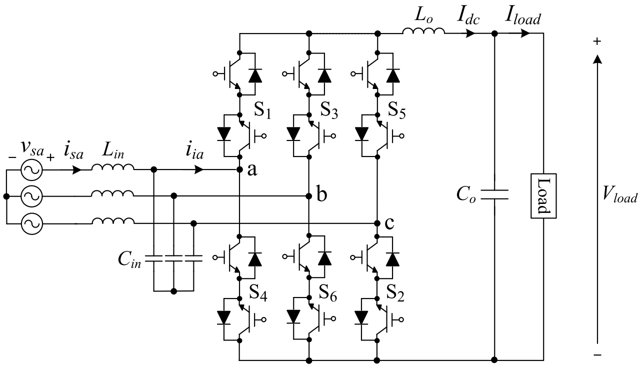

FIGURE 2. Ac-to-dc matrix rectifier.

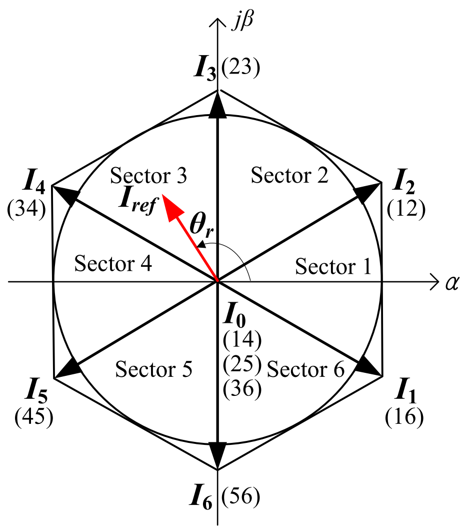

FIGURE 3. current space vectors according to the switching state of the matrix rectifier.

L_o and C_o are the inductance and capacitance of the output LC filter of the matrix rectifier, respectively; I_{dc} represents the current flowing through the output inductor L_o, and I_{load} and V_{load} respectively denote the current flowing into the dc load and the voltage applied to the load.

Ac-to-dc matrix rectifier described by Fig. 2 is generally controlled by SVM which is a technique using the current space vectors [9]. According to the switching state of the matrix rectifier, there are nine current space vectors including redundancy. Fig. 3 shows the current space vectors according to the switching state of the matrix rectifier. In Fig. 3, $\boldsymbol{I}_{\mathbf{x}}$ (x = 0, 1, 2, 3, 4, 5, and 6) means the current space vector. Also, $\boldsymbol{I}_{\boldsymbol{ref}}$ and θ_r represent the reference current space vector and the phase of the reference current space vector respectively. The number in parentheses below the current space vector denotes the on-state switch. The reference current space vectors in Fig. 3 can be implemented by three adjacent current space vectors during one sampling period. when the reference current space vector is in sector 1, the current space vectors of $\boldsymbol{I}_{\mathbf{0}}$, $\boldsymbol{I}_{\mathbf{1}}$, and $\boldsymbol{I}_{\mathbf{2}}$ are used for the rectifier control, and the dwelling time of each current space vector can be obtained by ampere-second balancing as follows (1). T_0, T_1, and T_2 in (1) represent the dwelling time of the current space vectors $\boldsymbol{I}_{\mathbf{0}}$, $\boldsymbol{I}_{\mathbf{1}}$, and $\boldsymbol{I}_{\mathbf{2}}$, respectively. Also, I_{ref} is the magnitude of the reference current space vector and T_s is the sampling period. For optimal switching performance, in each sector, different $\boldsymbol{I}_{\mathbf{0}}$ is used.

$$\begin{aligned} T_1 &= \frac{I_{ref}}{I_{dc}} \sin\left(\frac{\pi}{6} - \theta_r\right) T_s \\ T_2 &= \frac{I_{ref}}{I_{dc}} \sin\left(\frac{\pi}{6} + \theta_r\right) T_s \\ T_0 &= T_s - T_1 + T_2. \left(-\frac{\pi}{6} \le \theta_r < \frac{\pi}{6}\right). \end{aligned} \tag{1}$$

The input power factor of the ac-to-dc matrix rectifier is expressed as

$$\cos\phi = \frac{P_s}{\sqrt{P_s^2 + Q_s^2}} = \frac{P_s}{\sqrt{P_s^2 + (Q_{mr} + Q_c)^2}}. \tag{2}$$

here ϕ denotes the phase difference between the source voltage and the source current, and P_s and Q_s signify the active power and reactive power on the source side, respectively. The source-side reactive power Q_s can be represented by the sum of the rectifier-side reactive power Q_{mr} and the reactive power of the input capacitor Q_c, because the reactive power of the input inductance is negligible. To achieve a unity power factor on the source side, the reactive power generated by the matrix rectifier should fully compensate for the reactive power of the input capacitance, which implies that the sum of the rectifier-side reactive power and the reactive power of the input capacitor should be zero. The reactive power of the input capacitor is primarily dependent on the source voltage because the voltage drop across the input inductance is very small compared to the source voltage. In contrast, the amount of the reactive power that the rectifier can produce is restricted due to the limited modulation index for linear operations. Due to the limited reactive power supplied by the matrix rectifier, the matrix rectifier cannot operate at a unity input power factor, particularly during conditions of light loads.

The active power and the reactive power on the rectifier input side, P_{mr} and Q_{mr}, can be expressed by

$$\begin{bmatrix} P_{mr} \\ Q_{mr} \end{bmatrix} = \frac{3}{2} \begin{bmatrix} v_{s\alpha} & v_{s\beta} \\ v_{s\beta} & -v_{s\alpha} \end{bmatrix} \begin{bmatrix} i_{i1\alpha} \\ i_{i1\beta} \end{bmatrix}. \tag{3}$$

where $i_{i1\alpha}$ and $i_{i1\beta}$ are the fundamental components of $i_{i\alpha}$ and $i_{i\beta}$, respectively, which are the α and β axes current values of i_{ia}, i_{ib}, and i_{ic} in the *abc* stationary frame [26]. The modulation index of the matrix rectifier, m, can be calculated using the definition of the modulation index and (3) as

$$m = \frac{\sqrt{(i_{i1\alpha})^2 + (i_{i1\beta})^2}}{I_{dc}} = \frac{2V_{load}}{3P_{mr}} \sqrt{\frac{(P_{mr})^2 + (Q_{mr})^2}{(v_{s\alpha})^2 + (v_{s\beta})^2}}. \tag{4}$$

where $v_{s\alpha}$ and $v_{s\beta}$ are the α and β axes components of the three-phase source voltage v_{sa}, v_{sb}, and v_{sc}. Because the modulation index in (4) can vary from 0 to 1, the active power and the reactive power on the rectifier input side are

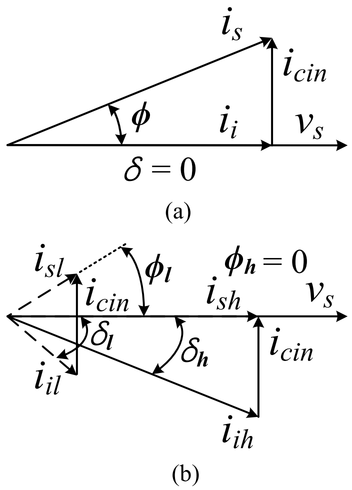

FIGURE 4. Vector diagram of input-side of the matrix rectifier (a) when power factor control is not applied and (b) when power factor control is applied.

restricted by the modulation index. When the load voltage and the rectifier input active power, which is equal to the dc load power by assuming no losses, are decided, the maximum reactive power of the matrix rectifier is restricted by the range of the modulation index. As a result, if the magnitude of the maximum reactive power that the rectifier can maximally produce is smaller than the magnitude of the reactive power of the input capacitor, the rectifier cannot generate a unity input power factor; in this case, the reactive power on the source side cannot be zero. Therefore, it is necessary to operate the matrix rectifier with a maximum power factor, which is less than unity. Consequently, a reference value of the source reactive power should be set to a nonzero value.

It can be known from a vector diagram that a unity power factor cannot be accomplished in the light load condition. Fig. 4 is a vector diagram of the voltage and current input-side of the matrix rectifier. In Fig. 4, ϕ, i_{cin}, and δ mean the angle between the source voltage and the source current, the current of the input capacitor, and the angle between the source voltage and the rectifier input current called the delay angle respectively. Also, the subscript h denotes the case of heavy load condition and the subscript i shows the case of light load condition. In Fig. 4, the voltage drop across the input inductor is neglected and only the fundamental component is considered. Due to the presence of the current of the input capacitor, without the power factor control, the input power factor does not become unity as shown in Fig. 4 (a). To accomplish a unity power factor, the magnitude of the rectifier input current and the delay angle is regulated. Equation (5) shows the relationship between the output power, the source voltage, and the rectifier input current. In (5), V_s and I_i means the peak magnitude of the source voltage and the rectifier input current respectively. Also, P_o is the output power.

$$P_o = 1.5 V_s I_i cos\delta. \tag{5}$$

Considering Fig. 4 (b) and (5), when the magnitude of the rectifier input current and the delay angle is increased, the phase of the source voltage and the source current can be matched by lagging the phase of the rectifier input current while maintaining the output power constant. It can be known from Fig. 4 that since the voltage drop in the input inductor is very small, the magnitude of the current flowing through the input capacitor is almost the same regardless of the load condition. However, as shown in Fig. 4 (b), because the magnitude of the rectifier input current and the delay angle that can be increased is limited, a unity power factor cannot be achieved under the light load condition [12]–[14].

In this paper, an algorithm that determines a reference value of the source reactive power to obtain the maximum input power factor online without any model parameter is proposed.

III. PROPOSED DIRECT POWER CONTROL WITH MINIMUM SOURCE REACTIVE POWER REFERENCE FOR MATRIX RECTIFER

The source active power P_s and the source reactive power Q_s are calculated as

$$\begin{aligned} P_s &= 1.5(v_{s\alpha} i_{s\alpha} + v_{s\beta} i_{s\beta}), \\ Q_s &= 1.5(v_{s\beta} i_{s\alpha} - v_{s\alpha} i_{s\beta}). \end{aligned} \tag{6}$$

A reference value of the source active power can be obtained from a proportional integral controller to regulate the dc-side current flowing into the output inductor of the rectifier, I_{dc}. On the other hand, a reference value of the source reactive power can be set to zero for unity power factor operation, in general. However, the matrix rectifier cannot always achieve a unity power factor due to the input LC filter installed on the rectifier input side. Thus, the proposed DPC method changes the reference value of the source reactive power by calculating the minimum reactive power reference according to operation conditions. Using the determined minimum reactive power reference of the source, the proposed DPC method enables the matrix rectifier to operate at a unity power factor or an MAPF.

The minimum reactive power reference of the source is related to the maximum reactive power generated by the matrix rectifier, which varies on an output power condition, and the reactive power of the input capacitor. By assuming that the voltage drop across the input inductor at a low frequency of the source is negligible, the reactive power of the input capacitor can be calculated by the source voltage and the fundamental components of the current flowing into the capacitor. In addition, the fundamental components of the capacitor current can be calculated by the difference between the measured source current and the fundamental value of the rectifier input current, which can be replaced by the rectifier input current reference. The rectifier input current reference can be obtained from the output of the SVM block. Thus, the reactive power of the input capacitor can be calculated by

$$Q_c = 1.5(v_{s\beta}\left(i_{s\alpha} - i^*_{i\alpha}\right) - v_{s\alpha}\left(i_{s\beta} - i^*_{i\beta}\right)). \tag{7}$$

TABLE 1. Determination of source reactive power reference base on $Q_{mr(max)}$ and Q_c.

	Source reactive power reference
$Q_{mr(max)} \geq \lvert Q_c \rvert$	0
$Q_{mr(max)} < \lvert Q_c \rvert$	$Q_{mr(max)} + Q_c$

Moreover, the maximum reactive power, $Q_{mr(max)}$, that the matrix rectifier can generate can be calculated based on the fact that the reactive power produced by the rectifier is limited by the range of the modulation index as shown in (4). Once the active power of the matrix rectifier is set by the output power, the maximum reactive power generated by the rectifier is restricted by the modulation index to be less than unity. Because the active power of the source is equal to the active power of the matrix rectifier, the maximum reactive power generated by the rectifier can be obtained, from (4), by

$$Q_{mr(max)} = \sqrt{\left(\frac{3}{2}I_{dc}\right)^2 \left((v_{s\alpha})^2 + (v_{s\beta})^2\right) - (P_s^*)^2}. \quad (8)$$

By comparing the reactive power of the input capacitor in (7) and the maximum reactive power of the matrix rectifier in (8), a source reactive power reference can be determined as presented in Table 1. A condition in which $Q_{mr(max)}$ is greater than or equal to the magnitude of Q_c implies that the matrix rectifier can fully provide the reactive power of the input capacitor. As a result, the source requires no reactive power command and the source reactive power reference is set to zero. In contrast, if $Q_{mr(max)}$ is less than the magnitude of Q_c, it means that the maximum reactive power, which the matrix rectifier can supply on a given condition, is not sufficient to entirely compensate for the capacitor reactive power. Thus, an additional reactive power should be provided by the source. Consequently, this condition yields an MAPF operation, because a unity power factor operation is not possible. The source reactive power reference should be minimal to obtain a maximum power factor, although the power factor is not unity. The minimum reactive power reference of the source can be calculated as the sum of the reactive power of the input capacitor and the maximum reactive power of the matrix rectifier, as indicated in Table 1.

The input power factor can be calculated, depending on the unity power factor or the MAPF operation, as

$$\text{Input power factor} = \begin{cases} 1, & Q_{mr(\max)} \geq |Q_c| \\ \dfrac{P_s}{\sqrt{P_s^2 + (Q_{mr(\max)} + Q_c)^2}}, & Q_{mr(\max)} < |Q_c|. \end{cases} \quad (9)$$

Fig. 5 shows the block diagram of the proposed DPC method with a minimum source reactive power reference. The proposed method can ensure that the matrix

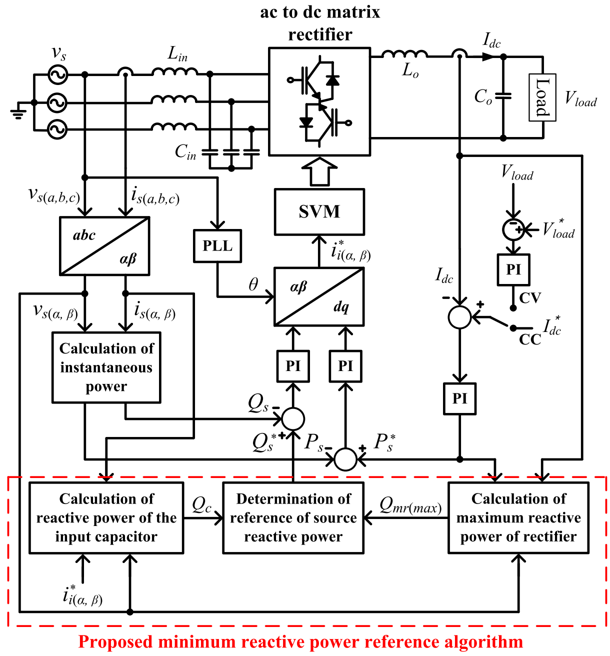

FIGURE 5. Block diagram of proposed DPC method with minimum source reactive power reference.

rectifier can work at a unity power factor or an MAPF at any operating condition, by instantaneously determining the minimum source reactive power reference. Additionally, it is clearly seen that the proposed algorithm can maximize the input power factor without using any circuit parameter; thus, it is free from any circuit parameter uncertainties.

The input power factor of the source is related to the reactive power of the capacitor, the maximum reactive power of the rectifier, and the source active power as indicated in (9). Thus, the input power factor is affected by the input capacitance, input voltage, output current, and output voltage. This study shows an explicit relationship of the input power factor according to the input capacitance and the dc output quantity. Because the voltage drop across the input inductor is negligible, the capacitor voltage can be assumed to be equal to the source voltage. As a result, the source active power, the active power of the matrix rectifier, and the reactive power of the matrix rectifier can be calculated as

$$P_s = P_{mr} = 1.5V_s I_{i1} \cos\delta = I_{dc}^2 R, \quad (10)$$
$$Q_{mr} = 1.5V_s I_{i1} \sin\delta, \quad (11)$$

where V_s, I_{i1}, δ, and R denote the peak value of the source voltage, peak value of the fundamental component of the rectifier input current, phase difference between the source voltage and fundamental component of the rectifier input current, and load resistance, respectively. It can be observed from (4) that the maximum reactive power of the matrix rectifier, $Q_{mr(\max)}$, occurs when the modulation index is 1. Therefore, during the operating condition when the rectifier supplies the maximum reactive power, the rectifier input

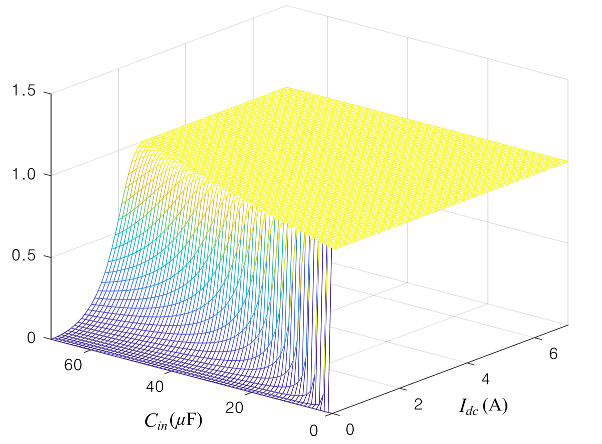

FIGURE 6. Relationship of input power factor with input capacitance C_{in} and output dc current I_{dc} ($V_s = 100$V, $R = 18.5\Omega$, $\omega = 377$rad/s).

current I_{i1} is equal to the output dc current I_{dc}, and thus, δ can be expressed from (10) as

$$\delta = \cos^{-1}\left(\frac{I_{dc}R}{1.5V_s}\right). \tag{12}$$

Thus, the maximum reactive power of the matrix rectifier can be represented by

$$Q_{mr(\max)} = 1.5V_sI_{dc}\sin\left(\cos^{-1}\left(\frac{I_{dc}R}{1.5V_s}\right)\right). \tag{13}$$

In addition, the reactive power of the input capacitor can be expressed by

$$Q_c = -1.5\omega C_{in}V_s^2, \tag{14}$$

where ω means the angular frequency of the source voltage.

Fig. 6 shows a graph of the input power factor with respect to the input capacitance and output dc current, derived using (9), (10), (13), and (14). The figure shows that the MAPF operation, instead of the unity power factor operation, is achieved at a light load condition, by the matrix rectifier with a small dc output current. Furthermore, as the input capacitance C_{in} increases, which yields an increased capacitor reactive power, the range of the unity power factor operation is reduced. This is because the larger the input capacitance, the larger the reactive power of the input capacitor, which must be compensated.

IV. SIMULATION RESULTS

Simulations were conducted to demonstrate the effectiveness of the proposed DPC technique with the minimum source reactive power reference of the matrix rectifier operated with a constant current mode. Table 2 presents the parameters used in the simulations and experiments. Note that the parameters for simulations and experiments were the same as those for the graph in Fig. 6, to clearly demonstrate the unity power factor and the MAPF operation depending on dc load conditions.

Fig. 7 shows the simulation results in a steady state when the dc reference current is set to 5 A. From the graph in Fig. 6,

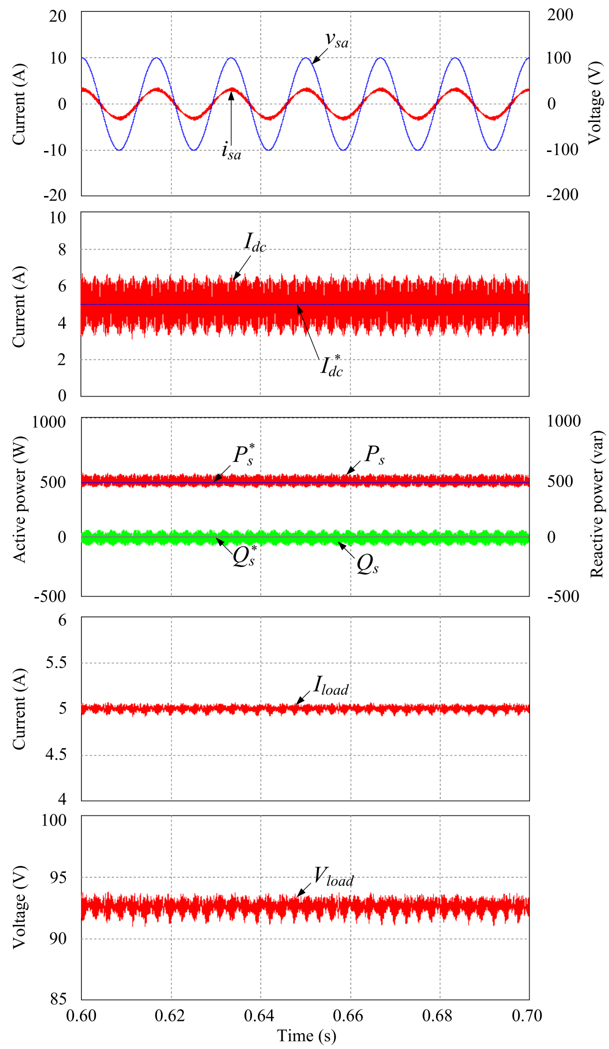

FIGURE 7. Simulation results in steady state with dc reference current of 5 A (unity power factor operating condition).

TABLE 2. Parametersused for simulations and experimensofac-to-dc matrix rectifie.

Parameter	Value
Input phase voltage V_s	100 V
Input voltage frequency f	60 Hz
Input inductance L_{in}	1 mH
Input capacitance C_{in}	60 μF
Output inductance L_o	2 mH
Output capacitance C_o	40 μF
Load resistance R	18.5 Ω
Sampling frequency	5 kHz

it can be observed that the matrix rectifier on this dc load current condition can operate at a unity power factor. Based on the proposed method with the minimum source reactive power reference, the source reactive power reference Q_s^* is set to zero by the controller as shown in Fig. 5, which is

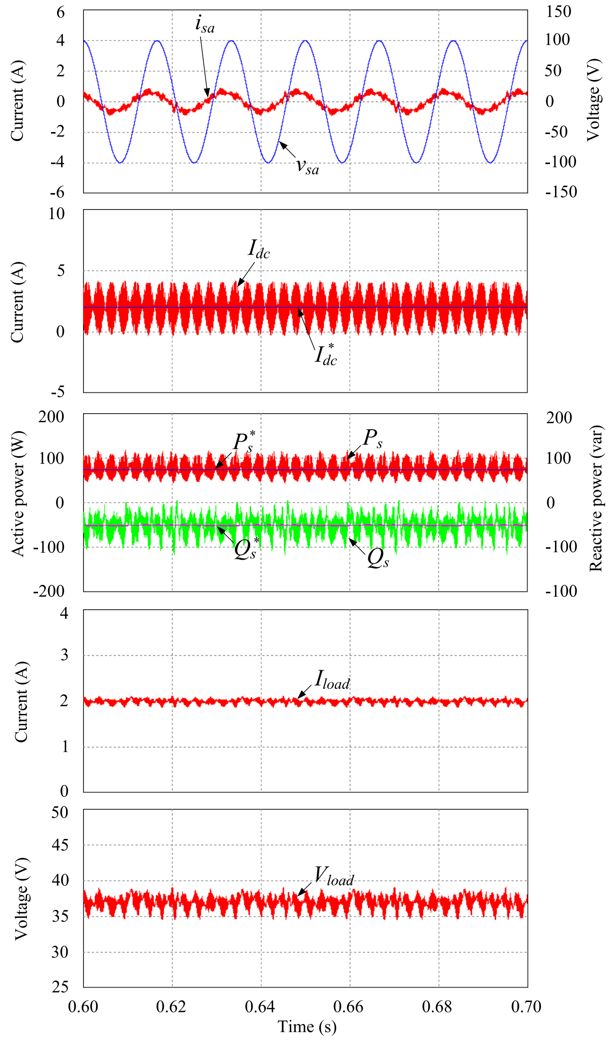

FIGURE 8. Simulation results in steady state with dc reference current of 2 A (MAPF operating condition).

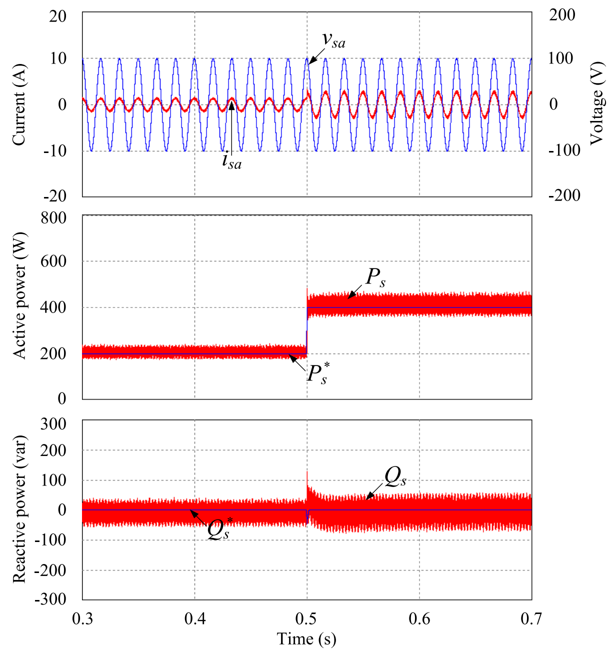

FIGURE 9. Simulation results with step change of source active power reference from 200 W to 400 W of proposed DPC method.

confirmed by the waveform of Q_s^* in Fig. 7. Thus, the proposed method generates the sinusoidal source current, which is in phase with the source voltage, leading to a unity power factor as shown in Fig. 7. Moreover, the actual active power and actual reactive power of the source are accurately regulated by the reference values through the proposed DPC method. It is observed that the dc current flowing through the output inductor is controlled by its reference. Furthermore, it is shown that the load current through the dc load and the load voltage are maintained well according to the required dc values.

Simulation waveforms in a steady state with the dc reference current of 2 A are illustrated in Fig. 8. This dc load current value corresponds to the MAPF operating condition, instead of the unity power factor operation as shown in Fig. 6. The proposed method instantaneously determines the minimum source reactive power reference of −50 var, based on a calculated Q_c of −340.5 var and $Q_{mr(max)}$ of 290.5 var from (7), (8), and Table 1, to maximize the input power factor. Therefore, the source reactive power reference Q_s^* was set to −50 var as shown in the waveform of Q_s^* in Fig. 8. Due to the nonzero source reactive power to partially compensate for the capacitor reactive power, the source current with a leading angle with respect to the source voltage is synthesized by the rectifier, as shown in Fig. 8. The source current in Fig. 8 appears distorted because the fundamental component of the source current is reduced for the power factor control. It is also seen that the actual source active and reactive power components achieved by the matrix rectifier operated by the proposed DPC method precisely follow their reference values. Moreover, Fig. 8 shows that, on the MAPF operating condition, the dc inductor current I_{dc} is accurately regulated by its reference value, and the load current/voltage is maintained well according to the required dc values.

Fig. 9 shows the dynamic performance of power control by using the proposed DPC method by directly changing the source active power reference value, while the reference of the source instantaneous reactive power is maintained at zero. As shown in Fig. 9, the active power tracking capability of the proposed DPC method is fast, while the active and reactive power components show a little coupling. Due to the increased source active power, the magnitude of the source current increases. In addition, because the source reactive power is controlled to zero, the phase of the source current is regulated in phase with the source voltage before and after the step change of the source active power.

Fig. 10 shows that when the reference of the source active power is maintained at 400 W, the step change of the reference of the source reactive power occurs. From Fig. 10, it can be observed that the source active power and reactive power track the reference well with no coupling effects before and after the step change. The phase difference between the

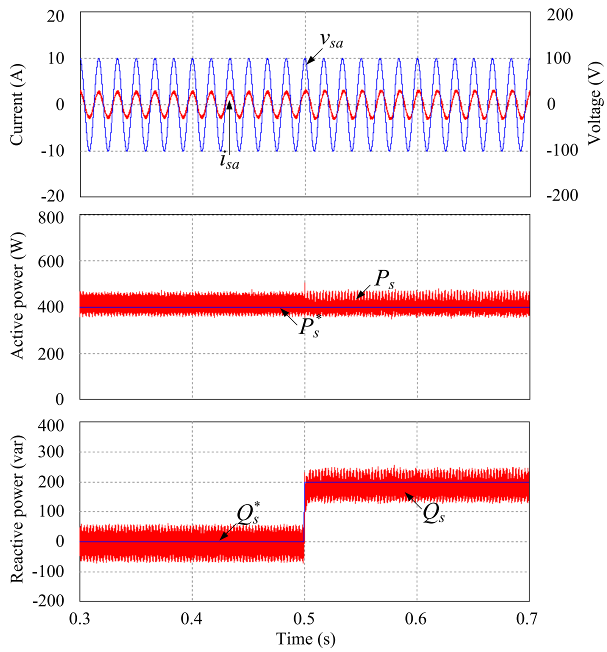

FIGURE 10. Simulation results with step change of source reactive power reference from 0 var to 200 var of proposed DPC method.

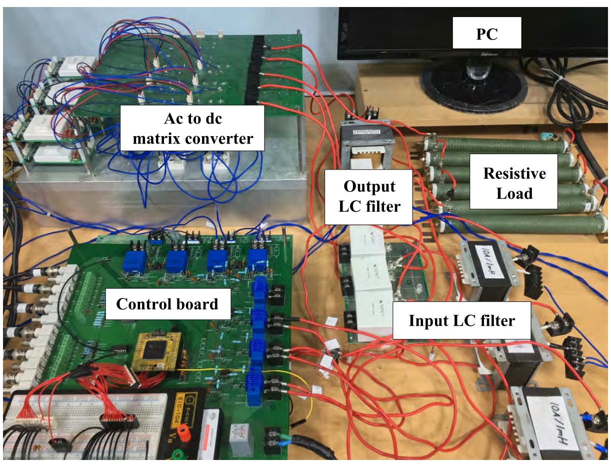

FIGURE 11. Experiment setup of ac-to-dc matrix rectifier.

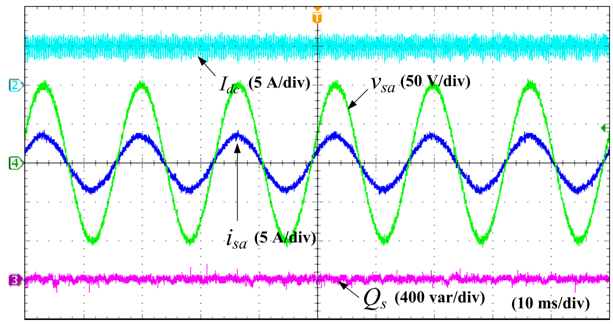

FIGURE 12. Experiment results of dc inductor current, *a*-phase source voltage, *a*-phase source current, and source reactive power in steady state when the dc reference current is set to 5 A (unity power factor operating condition).

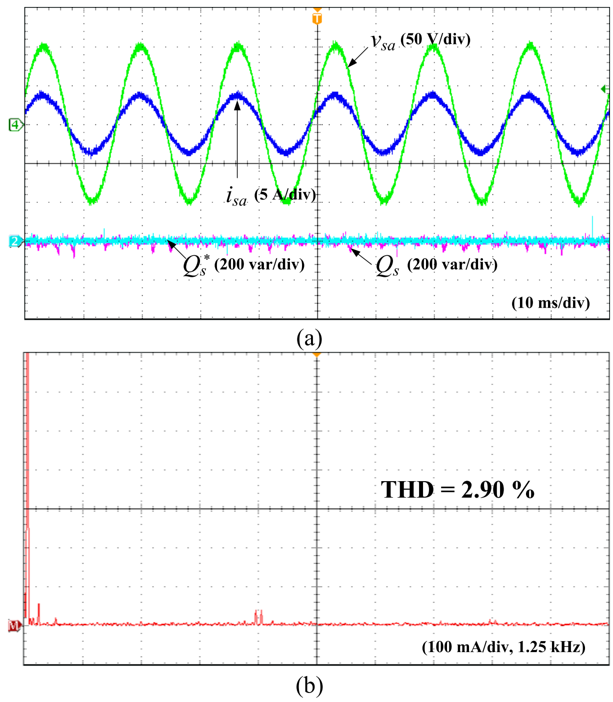

FIGURE 13. (a) Experiment results of *a*-phase source voltage, *a*-phase source current, actual source reactive power, and reference of source reactive power in steady state and (b) frequency spectrum of *a*-phase source current when the dc reference current is set to 5 A (unity power factor operating condition).

source voltage and current for the proposed method undergoes a change, depending on the reactive power reference, where the source current is lagging behind the source voltage after the step change of the source reactive power.

V. EXPERIMENT RESULTS

To demonstrate the effectiveness of the proposed DPC method with the minimum source reactive power reference for matrix rectifiers, experiments were conducted using a prototype setup. Bidirectional insulated-gate bipolar transistor modules (SK80GM063) and a digital signal processor board (TMS320F28335) were used for the setup. The parameters used in the experiment are the same as those in the simulations (see Table 2). Fig. 11 shows the experiment setup of the ac-to-dc matrix rectifier.

Fig. 12 shows the experiment results in a steady state when the dc reference current is set to 5 A, which corresponds to the unity power factor condition of the simulation results in Fig. 7. From Fig. 12, it can be observed that the actual dc inductor current is regulated to 5 A, and the source reactive power is controlled to zero. It can be confirmed that there is no phase difference between the source voltage and the source current.

From Fig. 13 (a), it can be seen that the reference value of the source reactive power is set to zero, because the matrix rectifier works at the unity power factor. From Fig. 13 (b), it can be observed that the source current has a lower total harmonic distortion and constant switching frequency.

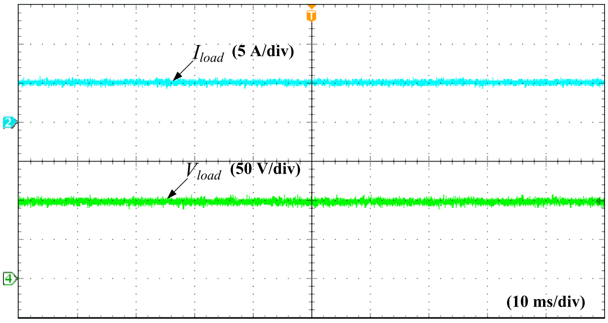

FIGURE 14. Experiment results of load current and load voltage in steady state when the dc reference current is set to 5 A (unity power factor operating condition).

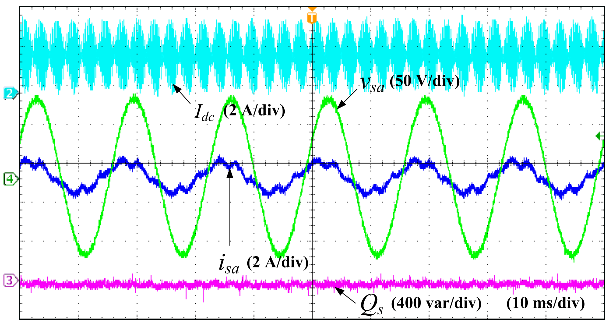

FIGURE 15. Experiment results of dc inductor current, *a*-phase source voltage, *a*-phase source current, and source reactive power in steady state when the dc reference current is set to 2 A (MAPF operating condition).

From Fig. 14, it can be seen that the load current and the load voltage are maintained at a constant value, where ripples of the load current and load voltage are almost zero.

Fig. 15 shows the experiment results in a steady state when the dc reference current is set to 2 A, which corresponds to the MAPF condition of the simulation results in Fig. 8. Due to the MAPF operating condition, the source reactive power reference is set to minimum by the proposed algorithm, instead of zero. Therefore, a nonzero phase difference between the source voltage and the source current exists. In addition, the dc inductor current is regulated to 2 A according to its reference value. The source current in Fig. 15 is less sinusoidal compared to that in Fig. 12, which is in the unity power factor condition. As already mentioned, the reduction in the fundamental component of source current results in a less sinusoidal waveform.

Different from Figs. 12 and 13, which correspond to the unity power factor operating condition, in Fig. 16 (a), the reference of the source reactive power is set to a nonzero value owing to the MAPF operation. Moreover, the actual source reactive power follows the reference value accurately. Fig. 16 (b) shows the frequency spectrum of the source current. It can be confirmed from Fig. 16 (b) that a less sinusoidal waveform is derived from the reduction in the fundamental component rather than the increase in harmonic component.

From Fig. 17, it can be seen that the dc load current is well regulated to 2 A, and the dc load voltage is maintained at a constant value.

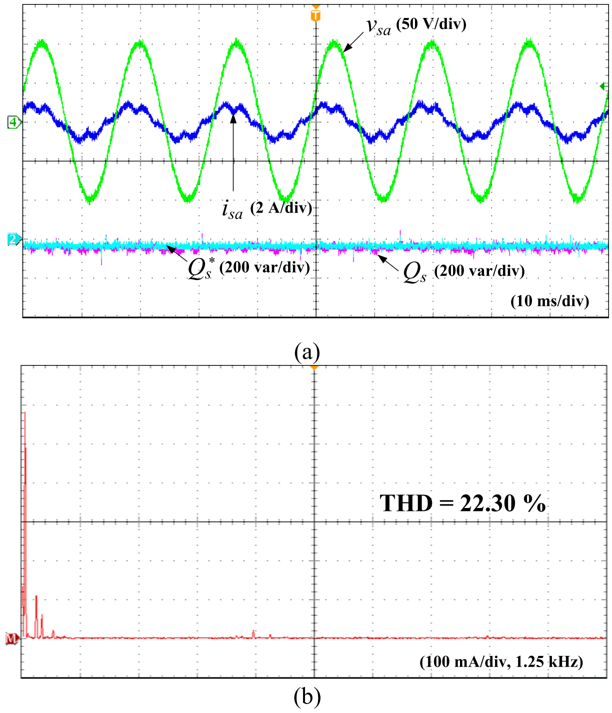

FIGURE 16. (a) Experiment results of *a*-phase source voltage, *a*-phase source current, actual source reactive power, and reference of source reactive power in steady state and (b) frequency spectrum of *a*-phase source current when the dc reference current is set to 2 A (MAPF operating condition).

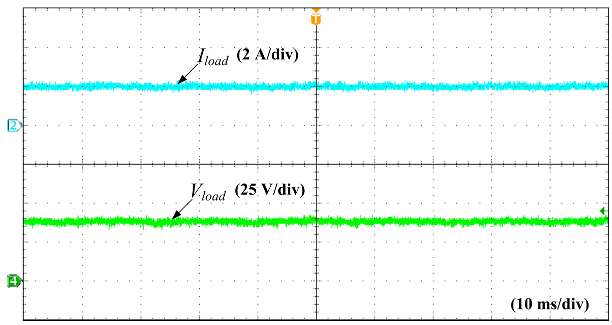

FIGURE 17. Experiment results of dc load current and load voltage in steady state when the dc reference current is set to 2 A (MAPF operating condition).

The behavior of the matrix rectifier with the step change in the active power reference from 200 W to 400 W while the reactive power reference is set to zero is shown in Fig. 18. The proposed DPC method for the matrix rectifier shows a fast dynamic response with decoupled power components. Because the reference of the source reactive power is set to zero, the experimental waveforms show that the source voltage and the source current are in phase before and after the step change. Due to the increased active power reference, the peak value of the source current increases after the step change.

Fig. 19 shows the dynamic response from the step change in the source reactive power reference from 0 to 200 var, with the source active power reference kept constant. It is observed

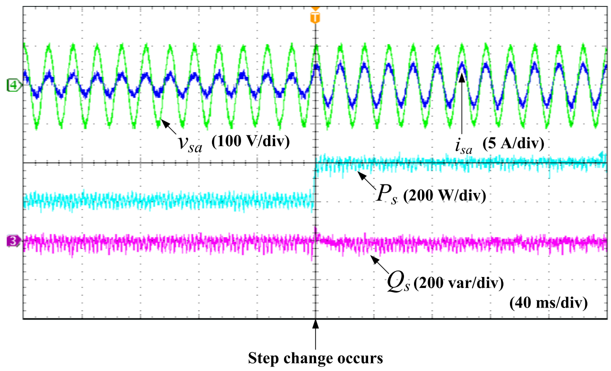

FIGURE 18. Experiment results of *a*-phase source voltage, *a*-phase source current, actual source active power, and actual source reactive power with step change of source active power reference from 200 W to 400 W of proposed DPC method.

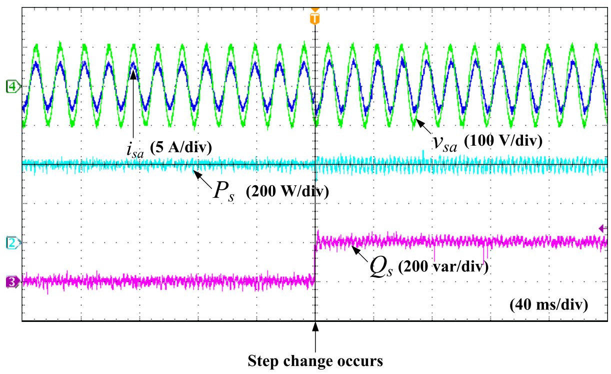

FIGURE 19. Experiment results with step change of source reactive power reference from 0 var to 200 var of proposed DPC method.

that the proposed DPC method of the matrix rectifier provides a fast tracking ability and decoupled performance between the power components, in the case of a sudden change in the reactive power reference. From Fig. 19, it can be observed that due to the step change of the source reactive power reference, the source current is lagging behind the source voltage after the step change. From Fig. 12 to Fig. 17, it can be concluded that the proposed DPC method with the minimum source reactive power reference can attain the unity power factor operation when circuit conditions are possible, or the MAPF operation by setting the source reference to a minimum value to achieve the maximum source power factor. Furthermore, it is verified that the reference tracking capability of the actual active and reactive power components is satisfactorily fast and decoupled.

VI. CONCLUSION

In this paper, a DPC method with minimum reactive power reference for ac-to-dc matrix rectifiers using SVM was proposed. The developed DPC algorithm directly controls both the active and reactive power components of the source in a decoupled manner based on the calculated active and reactive power reference values. Thus, sinusoidal input currents and the output dc voltage/current of the three-phase matrix rectifier are obtained. In addition, the proposed DPC method instantaneously determines a source reactive power reference command to achieve a unity input power factor or an MAPF on given input and output conditions, because ac-to-dc matrix rectifiers cannot always accomplish a unity power factor due to the existence of input capacitors. Furthermore, the developed algorithm calculates the minimum reactive power reference without using any circuit parameters. Thus, the proposed algorithm is free from any inevitable parameter uncertainty, which leads to a more robust and accurate power factor control for the rectifier. Based on the minimum reactive power reference, the proposed algorithm enables matrix rectifiers to operate at an input power factor that can be maximally obtained at all times. The effectiveness of the proposed method was validated by simulations and experiments.

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